DEEP SPACE EXPLORATION SYSTEMS

Artemis 1 Schedule Risk Assessment
Cost & Schedule Symposium
August 2019

Schedule Risk Assessment (SRA) Goals & Agenda

GOALS

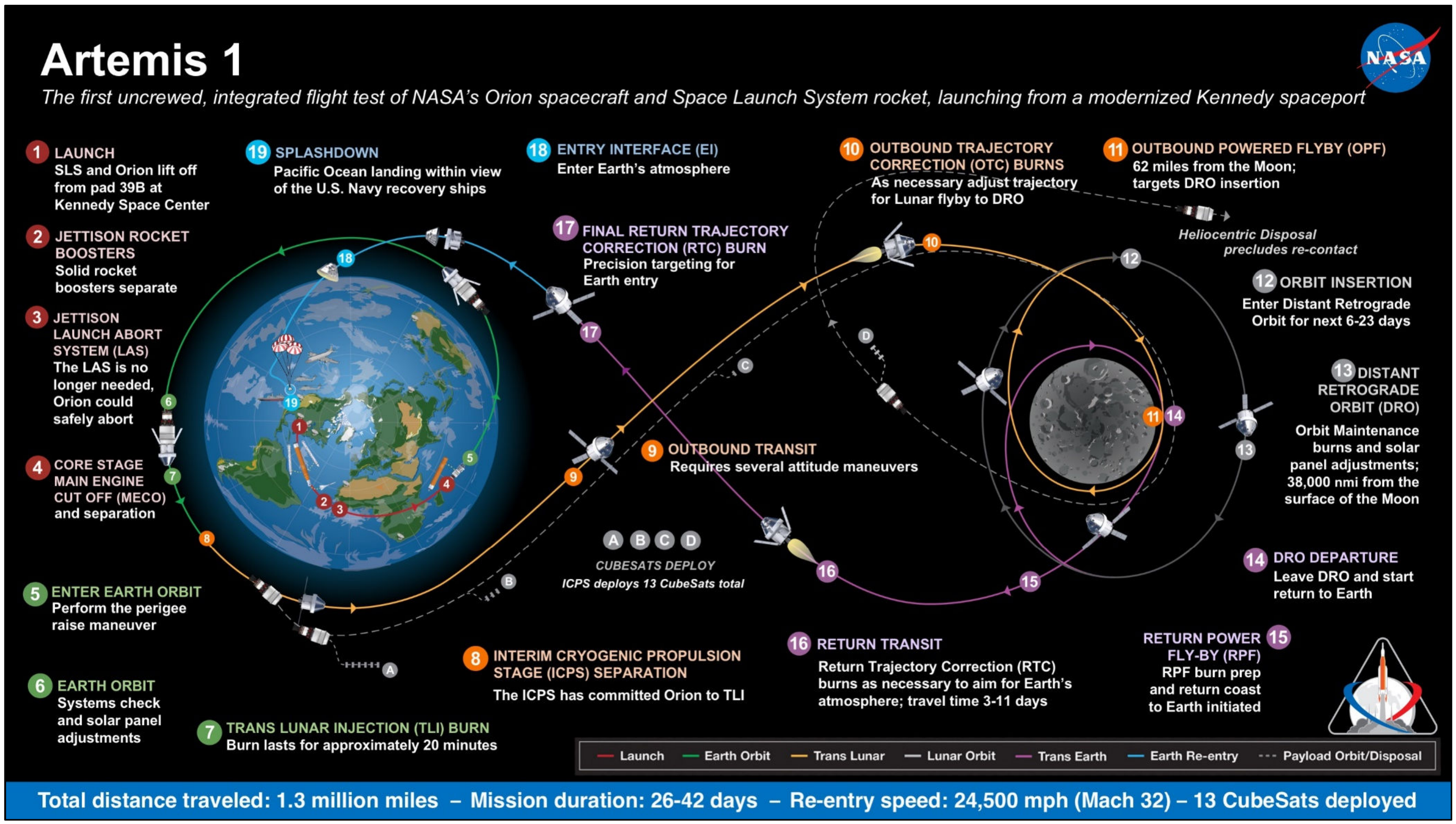
This brief covers **methodologies and lessons learned i**n a successful effort to develop an integrated Schedule Risk Assessment for Artemis 1 for other programs to leverage

Program results and inputs are not shown

AGENDA

- Artemis 1 Overview
- Enterprise Schedule Risk Assessment Summary & Impact
- Modeling Techniques
- SRA Results Briefing Format
- Lessons Learned
- Questions & Discussion

Artemis 1 Mission Overview (Previously EM-1)



Artemis 1 will be the first integrated test of NASA's deep space exploration systems: the Space Launch System (SLS), Orion spacecraft, and Exploration Ground Systems (EGS).

The three programs are integrated at the enterprise level.

Artemis 1 is focused on successful launch, orbit of the moon, and safe recover of the unmanned crew capsule.

Artemis 2 is a planned crewed mission.

Artemis 3 is a planned lunar landing

Artemis Organizational Structure & SRA Contributors

Over 30 contributors!

Exploration Systems Development (ESD)

SLS
- Keith Heitzman
- Jacquelyn Gower
- Mark Bryant
- Joe Hatchett
- Steve Patterson
- Mike Self
- Minda Alexander
- John Isom

Orion
- Ethan Miller
- Mike Stelly

EGS
- Nate Rychlik
- Trey Reilly
- Antonio Rippe
- Stan Hoback
- Joy Mosdell
- David Pierce
- Glenn Vera

- Tonya Mcnair
- Tom Rathjen
- Heide Borchardt
- Kelly Moses
- Aidan Flattery
- Laura Emerick Krepel
- Ashley Peter
- Maddy Sacripanti
- Chris McKelvey
- Thomas Beard
- Michael Call
- Eric Boulware
- Justin Hornback
- Stephen Bauder
- Dan Mulligan

- The Exploration Systems Development (ESD) organization is responsible for managing and integrating the three programs (SLS, Orion, & EGS) developing the specific capabilities needed to support deep space exploration
- The programs conduct their own schedule assessments which are leveraged alongside ESD analysis for this effort

Enterprise Schedule Risk Assessment Summary

	Initial Build	Integrated Model	Independent Evaluation	Quarterly Updates & Evals
Approach	• Developed high level integrated model with small team (4) and existing data • Performed Oct 2017- Jan 2018	• Developed more detailed model with program schedulers, risk managers, and analysts • Integrated data from individual program's SRAs	• Independent evaluation by OCFO Strategic Investment Division (Pirtle & King)	• Update quarterly or as required • Continually refine & improve modeling • Performing what-ifs & deep-dives
Accomplishments	• Briefed and shared results with leadership & broader team for detailed feedback	• Culminated with a brief to all program managers at the Nov 2018 Quarterly Program Status Review (QPSR) in a closed door executive session	• SID positively assessed: ○ Program & Enterprise schedule management practices ○ SRA uncertainty & risk assessments ○ Management use of SRA	• Consistent updates allow for clear insight into the impact of ongoing risk mitigation efforts • Regular leadership briefing of upcoming high-risk schedule areas and probabilistic critical paths • Shifted discussion from the model inputs & results into management actions, the "Now What"

- Senior NASA Leadership has called the Artemis 1 SRA the "gold standard" in NASA
- Management is using the SRA to inform schedule planning, decision making, and contractor management

Schedule Risk Assessment Overview

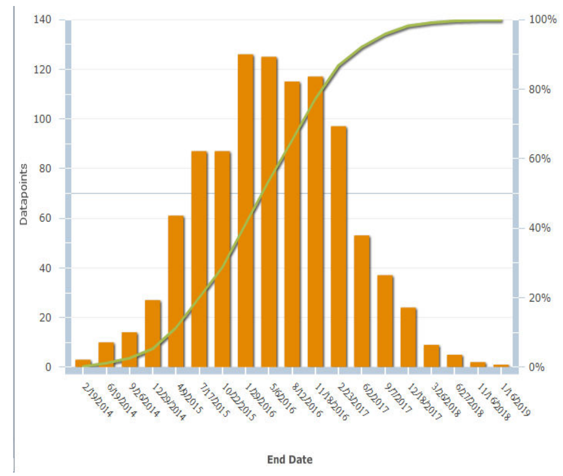
Input & Analysis

- **Schedule**
  - IMS or higher-level analysis schedule
  - Logically driven
  - Compatible with MS Project or Primavera P6
- **Duration Uncertainty Bounds**
  - Min, max & most likely durations of activities
- **Risks**
  - Probability of occurrence
  - Cost & schedule impacts if realize
  - Impact mapped to schedule task
- **Correlation**, other inputs

Monte Carlo
(Polaris)

X 1,000 – 15,000
Simulation Runs

Output & Results



Result is a probabilistic finish date
50 % chance of finishing by…
70 % chance of finishing by…

Schedule Risk Assessment quantifies the combined impact of duration uncertainty and project risks.
It provides ***predictive and actionable*** programmatic insights and data confidence.

SRA Modeling Techniques

Modeling Techniques

A range of modeling techniques have been utilized based on the data available at each program

- **Discrete Event Simulation (DES):** Utilized the outputs from detailed program DES modeling. The DES model further incorporated input from historical data, subject matter experts, and historical learning curves
- **Historical Milestone Trending:** Trended historical performance data for the period available and identified the average rate of change (slip rate). Forecasted this rate of change forward to estimate delivery dates
- **Earned Value Management (EVM) Data:** Used program earned value data as a basis to construct uncertainty estimates Uncertainty estimates were generated using the earned schedule technique
- **Historical Performance Ratio:** Evaluated completed analogous activities from detailed program schedules, analyzing their actual duration / baseline duration
- **Regression:** Evaluated actual duration versus baseline duration for comparable activities
- **Subject Matter Experts (SMEs):** Incorporated duration uncertainty estimates from enterprise and program SME's
- **Other Performance Data:** Evaluated performance in terms of job burndown and Agile Point burndown

Ideally, multiple modeling methods can be used in order to compare and understand the impact to results

Existing Enterprise Schedule is the Basis for the SRA

THE INTEGRATED ENTERPRISE SCHEDULE, KNOWN AS THE ECS[1]:

- Is a cross-program analysis schedule that is based on a summary of each of the three program's integrated master schedules
- Is statused on a monthly basis by each of the programs and maintained & evaluated by the enterprise Programmatic & Strategic Integration Schedule Analysis Team (PSAT)
- Serves as the basis for agency integrated reporting including critical path analysis, delay evaluation & what-ifs
- Serves as the basis for both the ESD and SLS schedule risk assessments

ECS to SRA Analysis Schedule

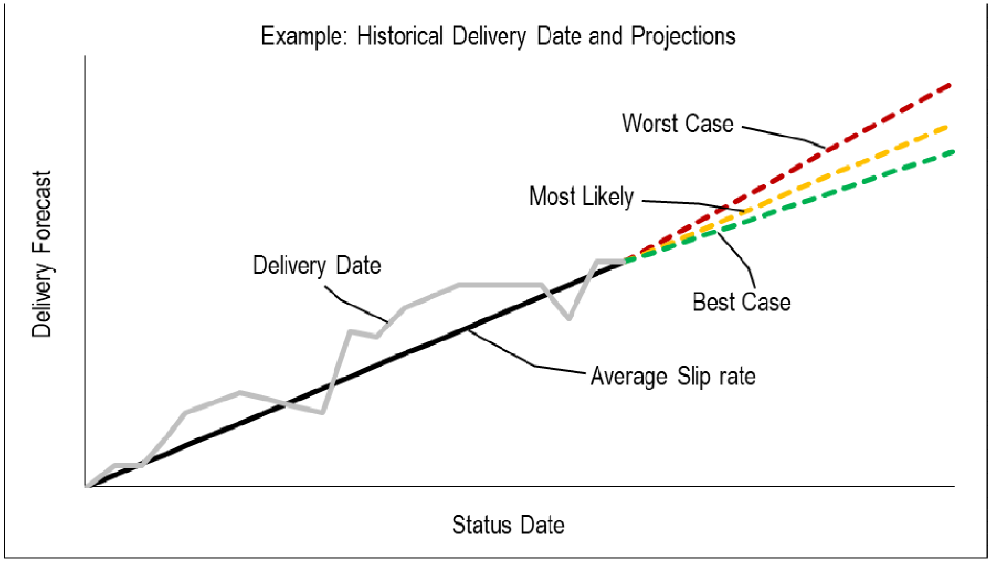
- Leverage a consistent calendar (we used 7 days, no holidays)
- Removed completed activities
- Omit items that are not expected to be on critical path to reduce model validation time
- Minimize the use of short-duration activities in Polaris due to rounding to whole days

SID confirmed that the ECS is an accurate representation of the programs' IMSs and lower level schedules

[1]ECS = Enterprise Cross-Program Integration Team Schedule.

Historical Milestone Trending

- Collected historical data for key delivery milestones and generated a trend line surrounding this
- Calculated the average rate of change (slip rate) over the given time series
- Used the average rate of change to generate uncertainty bounds:
  - **Worst Case**: 30% greater than the average rate of change
  - **Most Likely**: Forecasts the average rate of change forward
  - **Best Case**: 30% better than the average rate of change or the most recent forecasted delivery date
  - Typically performance does not deviate more than 20-30%

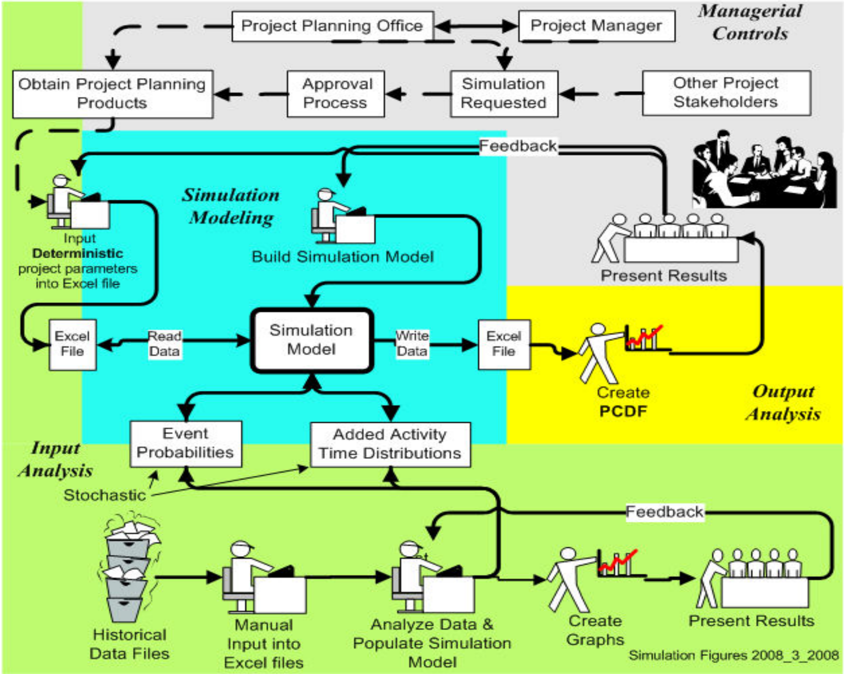


$$\text{Average Slip Rate te} = \frac{(\text{Current Forecasted Finish} - 1^{rst}\ \text{Finish})}{(\text{Current Status Date} - 1^{rst}\ \text{Status Date})}$$

Discrete Event Simulation (DES)

- The Exploration Ground Systems (EGS) Program uses discrete event simulation to model and analyze the planned ground ops at KSC.
- These models are used to analyze the potential impact of various risk factors on processing schedules, provide a framework for performing “what-if” analysis, and support architecture trade studies.
- **Modeling guidelines:**
  - **Model at the level of detail for which there is data**
  - **Model at the level of detail required to provide the answer**
  - **Complete the analysis in time**
- Planning products include:
  - Ground Ops Schedules
  - Launch Countdown Timelines
  - Mission Specific Launch Windows
  - Launch Vehicle, Spacecraft and Ground Architecture Assumptions
- Additional input sources:
  - Analogous Historical Data
  - Subject Matter Expert Input
  - EGS, SLS, Orion, and Natural Environments Analysis Products

Discrete Event Simulation is a modeling technique for complex and dynamic systems where the state of the system changes at discrete points in time and whose inputs may include random variables.



Discrete Event Simulation (DES)

ARTEMIS 1 OPS ANALYSIS

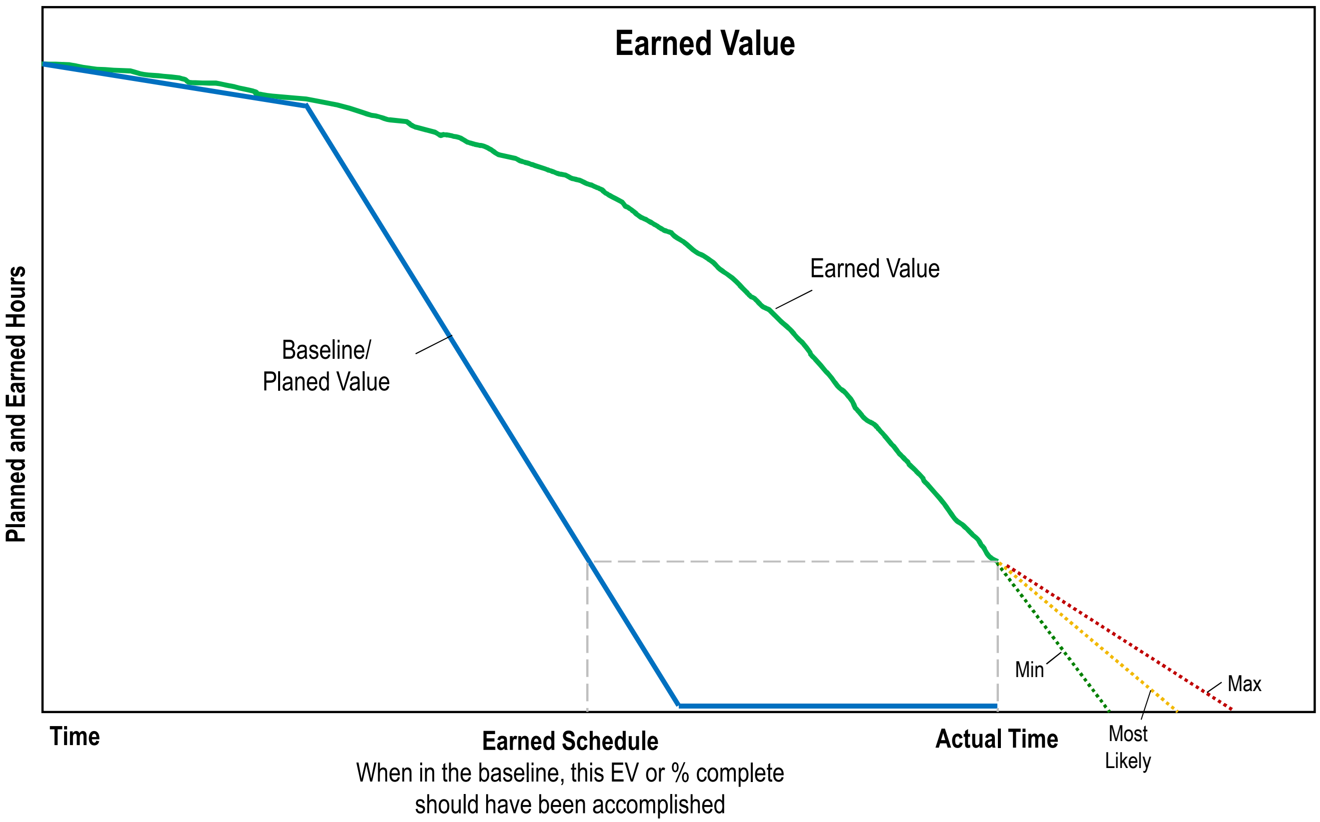
- There are a number of factors that could potentially cause the Artemis 1 target launch date to slip. EGS has undertaken an effort to identify, quantify, document, and mitigate the risks that could potentially impact the ground operations portion of the flow.
- Risk factors have been included to quantify the potential impact of:
    - **Common Cause Variability (Performance):** In order to estimate the potential impact of processing variability we utilize variable (based on the min, most likely, 95th %ile estimates) as opposed to deterministic input durations.
    - **Historical Delays and Program Inputs:** Delay probabilities and delay duration distributions have been derived from historical data for analogous operations as well as reliability estimates for flight hardware and ground systems.
    - **First Flow Specific Risks:** Additional potential growth for first time ops has been estimated based on assessing early Shuttle flows along with an assessment of the experience of the people, and the maturity of the parts and paper for specific operations.

FORWARD WORK AS WE APPROACH ARTEMIS 1 OPERATIONS

- Enhance underlying planning products and risk models using “as-run” data from pathfinder operations, MEVV, AA-2, etc.
- Utilize the model to provide timely analysis based on changing conditions (e.g. traveled work, element delivery dates, new requirements, non-conformances, etc.)

- Results from each simulation trial of the DES model are provided to ESD
- ESD fits a distribution to this data set and incorporates it as an input into the SRA

Earned Value

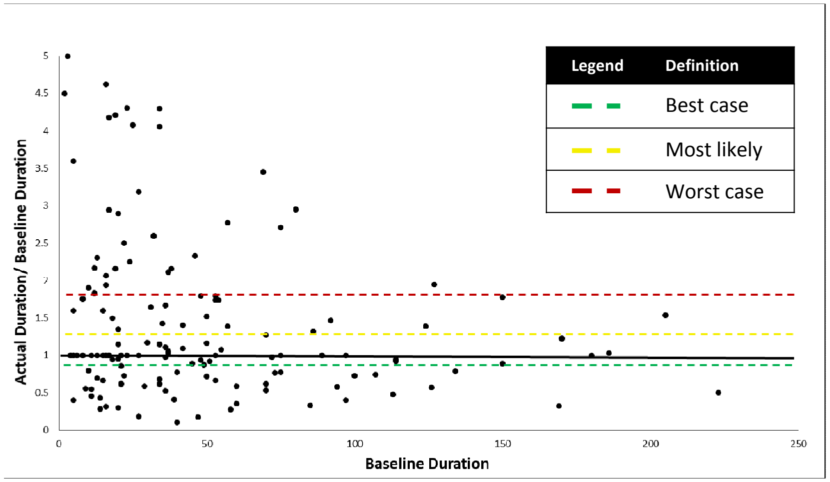


*Earned Schedule Technique: Actual time (duration) / Planned time (duration) in the baseline schedule to accomplish today's earned value. Project that ratio forward (Actual Time/ Earned Time). See http://www.earnedschedule.com/. Earned schedule resolves the issue that SPI always returns to 1.0 at the end of the project

- When available, earned value data served as the basis for uncertainty estimates
- Uncertainties were calculated as follows:
  - **Best Case –** Assumes return to baseline productivity or current completion date (whichever is later)
  - **Most likely –** Earned schedule technique*
  - **Worst Case –** Projects the historical rate of performance forward (straight line)
- The earned schedule method leverages EVM data to analyze a program's schedule status and forecast its completion

Actual Duration vs Baseline Duration for Analogous Tasks

- Worked with programs to review detailed schedules and identify activities analogous to future work
- All activities identified were completed by the same group who would also be completing the future work
- Analyzed historical actual performance relative to the baseline plan by generating a ratio from actual duration vs baseline duration
- Used a weighted average to mitigate the impact of short duration activities (weighted by baseline duration)
  - Short duration activities could skew the analysis in an overly pessimistic direction
- Limited the use of high duration activities as a majority of the activities in the data set had a duration under 50 days

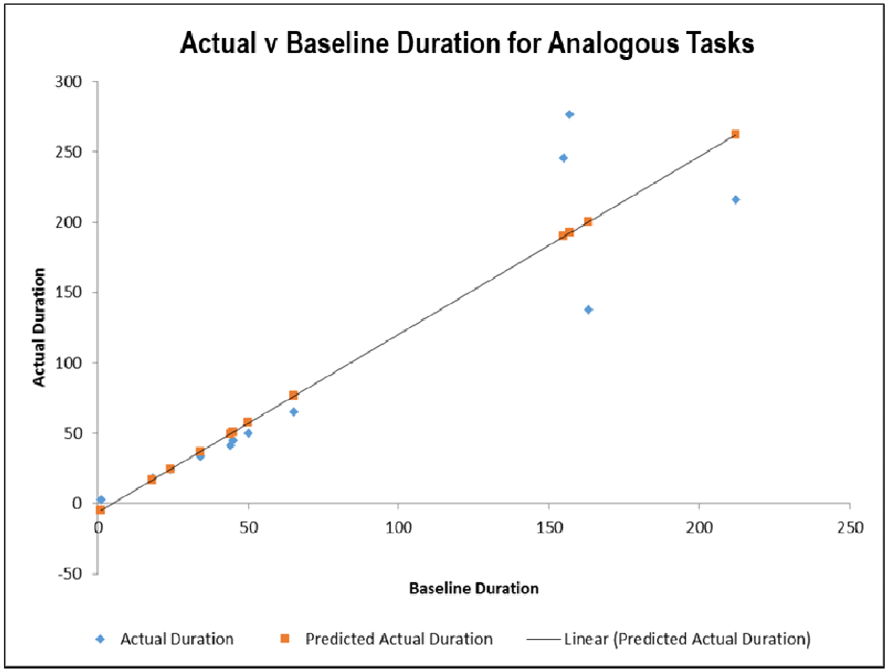


- Three point uncertainty estimates were generated as follows:
  - **Worst Case:** 75th percentile of performance ratio data
  - **Most Likely:** Weighted average of the performance ratio data
  - **Best Case:** 25th percentile of performance ratio data

$$\text{Performance Ratio} = \frac{\text{Actual Duration}}{\text{Baseline Duration}}$$

Actual Duration vs Baseline Duration - Regression

- Based upon actual duration vs baseline duration for analogous tasks
- Using excel, fit a linear regression curve to data



- Three point uncertainty estimates were generated as follows:
  - **Worst Case:** Upper 95% confidence interval
  - **Most Likely:** Regression "best fit"
  - **Best Case:** Lower 95% confidence interval

Task Name	Remaining Duration	Lower 95% (Min)	Regression (ML)	Upper 95% (Max)
-	-	Y = .905x - 20.1	Y = 1.05x - 4.5	Y = 1.30x + 15.1
Task 1	140	107	142	197
Task 2	100	70	100	145
Task 3	70	43	69	106

Subject Matter Expert

- Inputs were drawn from SMEs who possessed experience from similar projects or who were the most knowledge in the subject area
  - Did not ask just anyone on the street
- Generally, SMEs provided a three point estimate using the following criteria:
  - **Best Case:** Considers the opportunity to accelerate the schedule via de-scoping, applying additional resources (extra shifts, shifting staff), etc. (5% estimate); *"How quickly could this be worked if it were driving launch?"*
  - **Most Likely:** Estimates driven from task durations of similar projects on which the SMEs have direct experience
  - **Worst Case:** Assumes significant challenges with testing, integration, etc. (95% estimate). Not modeling catastrophic scenario within uncertainty estimates (can be done using risks)
- Ideally, in these scenarios, multiple SMEs with a range of experience were leveraged
  - Uncertainty estimates were developed as an aggregate of the varying inputs given In many scenarios, a data driven SME approach was utilized
  - The estimates were initially developed using historical data, then SMEs made adjustments to these estimates where needed

SME Inputs were drawn from those with the most experience
SMEs were asked to consider both acceleration opportunities (5%) and non-catastrophic worst-case scenarios (95%)

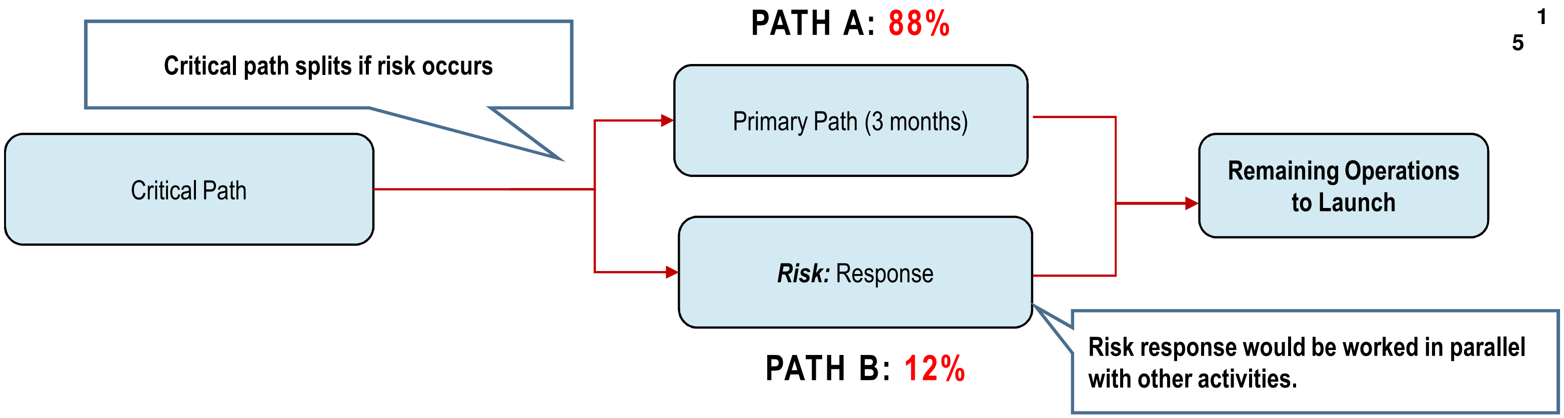
SRA Risk & Opportunity Modeling

- Reviewed 100+ enterprise, program, and cross-program risks and analyzed their probabilistic impact to launch
- Spent time with program risk SMEs and schedulers to:
  1. Ensure risks & duration uncertainty were not double counting
  2. Map risk impacts to the correct schedule tasks and ensure appropriate logic
  3. Understanding parallel versus in series activities

     "If this tests fails, could the corrective action be worked in parallel with next steps?"
  4. Validate impact to the model "Does this make sense?"
- Modelled acceleration opportunities

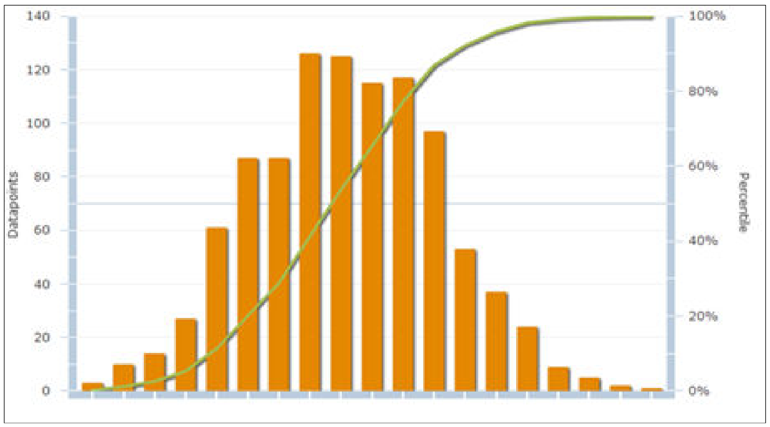
LIKELIHOOD	1	2	3	4	5
5	7	16	20	23	25
4	6	13	18	22	24
3	4	10	15	19	21
2	2	8	11	14	17
1	1	3	5	9	12

CONSEQUENCE



SRA Results Briefing Format

SRA Build & Updates: Briefing Results

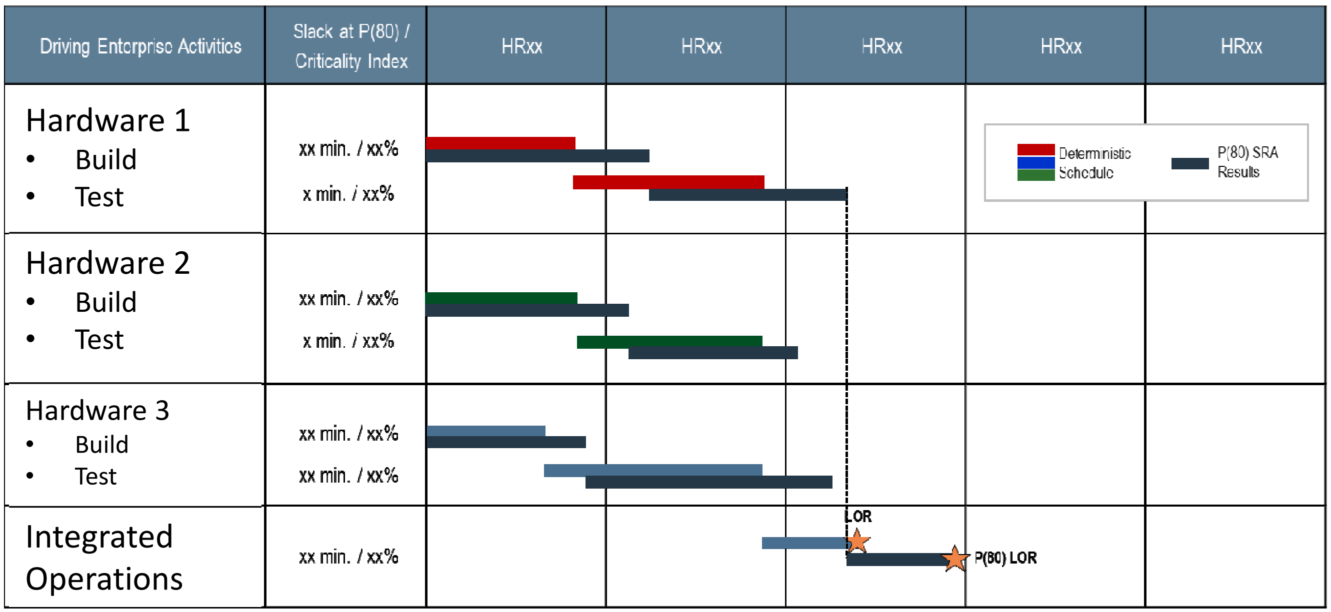


Milestone	Deterministic ECD	P(20)	P(50)	P(80)
Launch	xxx	Date +1.0 mo.	Date +2.0 mo.	Date +3.0 mo.
HW 1	xxx	xxx	xxx	xxx
HW 2	xxx	xxx	xxx	xxx
HW 3	xxx	xxx	xxx	xxx

Drivers to P(80) Launch	Incremental Impact (months)	Cumulative Impact (months)
Baseline Launch Date	-	-
+ HW 1 Duration Uncertainty	xx	xx
+ Integrated Test & Checkout Uncertainty	xx	xx
+ Risk	xx	xx
P(80) Launch	**xx**	

- Results focused on the 20/50/80 percentiles
  - P(80) selected to correspond with P(70) JCL requirements
  - SRA results shown as risk-adjusted date + delta to baseline or current schedule
- Driver chart builds up incremental impacts to launch
  - Enables viewer to adjust (or discount) a single driver and calculate the impact to launch
  - Developed by individually loading portions of the model, also helpful during validation

SRA Build & Updates: Briefing Results



- Colored bars of the Gantt chart represent the programs' deterministic schedule
- Black bars represent the probabilistic finish at P(80)
- Visualizes critical enterprise drivers to launch and which items have probabilistic slack
- Chart also provides :
  - **Probabilistic Slack:** Following the model being run, amount of slack to primary critical path milestone (in months)
  - **Criticality Index:** Percentage of 10,000 Monte Carlo runs that a task appeared on the critical path.

Tracking both probabilistic critical path and criticality index focuses attention on near-critical items

Near-Term Forecasts Over Time vs. SRA Predictions

ESD tracks near-term performance of key milestones against SRA results

Item	Latest Forecast
Item 1	xx/xx/xxxx (complete)
Item 2	xx/xx/xxxx (complete)
Item 3	xx/xx/xxxx (complete)
Item 4	xx/xx/xxxx (complete)

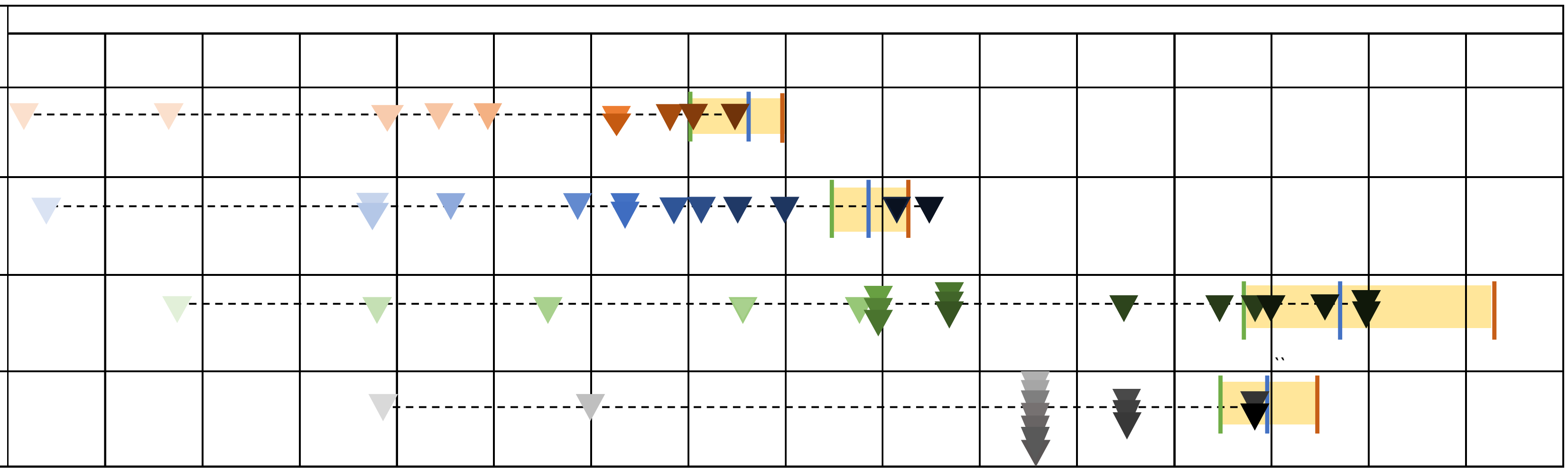
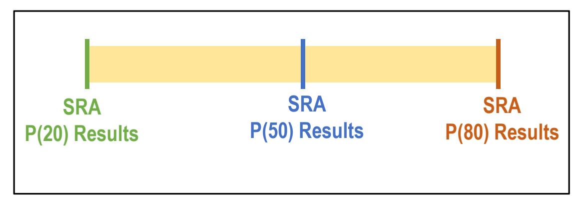


Table above shows forecasts of several key milestones projected completions over time (darkest colors represent latest forecasts). For comparison, SRA predicted results range is shown as gold bars



In many cases, our near-term SRA predictions have been accurate

Lessons Learned

Overall Impact of Artemis 1 SRA

IMPROVED MANAGEMENT FOCUS

- The Agency is using the SRA to focus management attention on key drivers and targeted areas of improvement
- The SRA has clarified program drivers, identified areas of uncertainty, improved our understanding and reporting of dependencies, integration points, and potential impacts to future missions
- The approach, results, and drivers were briefed and accepted by increasingly larger and more senior audiences, including Agency leadership

ENHANCED ANALYSIS CAPABILITIES

- Development of the SRA served as a catalyst for deeper schedule analysis and performance evaluation at both the enterprise and program levels
- The evolution of this analysis has helped to further foster relationships among the enterprise and program analysts, allowing for additional data and insights reported to the enterprise level

INCREASED REPORTING OF RISKS AND MITIGATIONS

- Provided Programs with additional insight into the cross-program impact of schedule risks, helping to focus mitigation resources on those risks which are truly program drivers

Lessons Learned

Key Content!

1. **Start simple**
    - Roll-up work to phases and to the level to which you have available data
    - Build an SRA model early based upon high-level assumptions if necessary
    - Show findings & assumptions & ask for feedback and additional information
2. Invest in understanding activities and “no kidding” dependencies
    - Identify margin
3. Conduct sensitivity analysis to focus on drivers
    - Dial-up/down duration uncertainty to see if it moves the “needle”
4. **Build your model based upon objective performance data, where possible**
    - Ideally leverage multiple different performance inputs
    - Look at performance over a sustained period “recent performance improvements” balance out over a 3-6 month rolling average
5. Consider acceleration and workaround opportunities
    - Ask, *“How quickly could this be worked if it were driving launch?”*
6. Minimal impact of correlation on results within the P(20)-P(80) range (1-4% impact)

Questions & Discussion